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SOURCE OF ATOMIC HYDROGEN IN THE ATMOSPHERE OF HD 209458b

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ABSTRACT

Atomic hydrogen loss at the top of HD 209458b's atmosphere has been recently suggested (Vidal-Madjar et al.). We have developed a one-dimensional model to study the chemistry in the upper atmosphere of this extrasolar "hot Jupiter." The three most abundant elements (other than He) as well as four parent molecules are included in this model, viz., H, C, O, H_2, CO, H_2O, and CH_4. The higher temperatures (~1000 K) and higher stellar irradiance (~6×10^5 W m^{-2}) strongly enhance and modify the chemical reaction rates in this atmosphere. The main result is that the production of atomic hydrogen in the atmosphere is mainly driven by H_2O photolysis, and the reaction of OH with H_2, and is *insensitive* to the exact abundances of CO, H_2O, and CH_4. For comparison, the bulk H concentration for "hot Jupiters" is 3 orders of magnitude higher than that of Jupiter.

Subject headings: planetary systems — radiative transfer — stars: atmospheres — stars: individual (HD 209458)

1. INTRODUCTION

Since the discovery of the first extrasolar planet, 51 Peg b, in 1995 (Mayor & Queloz 1995), a total of 102 planets have so far been discovered (e.g., Butler et al. 2003; Udry et al. 2002 and references therein) and analyzed statistically in order to characterize the formation environment (Fischer et al. 2002; Santos et al. 2003). The formation of gas giants is thought to be complete in 10 Myr, before the disappearance of the gaseous stellar accretion disk, at distances greater than 5 AU from the parent star. They are then pulled to their present positions by tidal interaction between the gas disk and the planet (e.g., Pollack et al. 1996; Ward 1997).

An edge-on planetary system provides a unique opportunity to investigate the planetary atmosphere. HD 209458b is such a planet, providing the first extrasolar planetary detection using the light curve obtained during a planetary transit of its parent star (Charbonneau et al. 2000; Henry et al. 2000). The orbital parameters were accurately determined by Charbonneau et al. (2000), Henry et al. (2000), and Mazeh et al. (2000). Strong absorption lines are required to make an atmospheric detection, and Seager & Sasselov (2000) theoretically characterized the most prominent absorption features, viz., Na I and K I doublet resonance and He I 2^3S–2^3P triplets. Charbonneau et al. (2002) detected the Na I doublet at 589.3 nm in HD 209458b with an ~4 σ confidence level. Following this, Vidal-Madjar et al. (2003) made the first observation of the extended upper atmosphere of HD 209458b with an ~4 σ detection of the H I atomic hydrogen absorption of the stellar Lyα line. They reported an absorption of ~15% ± 4% and claimed this should be taking place beyond the Roche limit, thus implying a hydrodynamic escape of hydrogen atoms from HD 209458b's atmosphere.

The temperature and UV flux of close-in planets are high. This motivates us to study the chemistry that may be important in this "hot Jupiter." In this Letter, we consider a simple hydrocarbon/oxygen chemistry model to determine the source of atomic hydrogen in the atmosphere of HD 209458b, and this represents the first effort to investigate the UV-enhanced chemical processes in "hot Jupiters."

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2. MODEL

Our model is based on the four parent molecules H_2, CO, H_2O, and CH_4 and is a derivative of the Caltech/JPL kinetics model for the Jovian atmosphere. HD 209458b is orbiting at a distance of 0.05 AU. Since HD 209458 is a G0 solar-type dwarf star, it is justified to use the solar spectrum. We expect the atmosphere to have a temperature of ~1000 K and UV flux of (<1800 Å) ~ 2×10^{15} photons cm^{-2} s^{-1}. By comparison, the UV flux at Jupiter is a factor of ~10^4 lower.

A one-dimensional radiative transfer model is applied to the atmosphere with 80 layers. The main UV absorber in this model is H_2O, ~100%. The strong UV absorbers, e.g., metals, are ignored in this study. A total of 253 chemical reactions involving C, H, and O molecules is taken from the literature. The reaction rates are determined from laboratory measurements made mainly at room temperature. In this work, the chemical reactions are at much higher temperatures. Without any accurate measurements of the reaction rates at high temperatures, we either adopt the derived temperature-dependent rate constant, which is measured at a lower temperature, or use the theoretical calculation for the temperature dependence (e.g., Yung & DeMore 1999).

Hydrocarbons.—The hydrocarbon photochemical scheme used here is a simplified version of the Jovian atmospheric model described in Strobel (1973) and Gladstone, Allen, & Yung (1996). The photodissociation of CH_4 and the subsequent reactions of the species with hydrogen produce all the other hydrocarbons present in a Jovian-type atmosphere. For lower temperatures and weaker stellar irradiation, the main source of H is from H_2 and CH_4 photodissociation, and the main sink via C_2H_2, which acts as a catalyst in recombining H. HD 209458b receives much greater stellar irradiation and is therefore much hotter than Jupiter. In this case, the formation of H is greatly enhanced by photolysis of H_2O and reactions between O and OH radicals and H_2. The sink for H is more complex (see § 3.3).

Oxygen.—O is similar in abundance to C and represents a cosmic abundance of the parent molecules. The atmospheric H_2O abundance will be controlled mainly by the comparative richness of these two species. The amount of H_2O and CO governs the amount of atomic oxygen present, and the related reactions are of great interest. The oxygen-related reactions are taken from Moses et al. (2000).

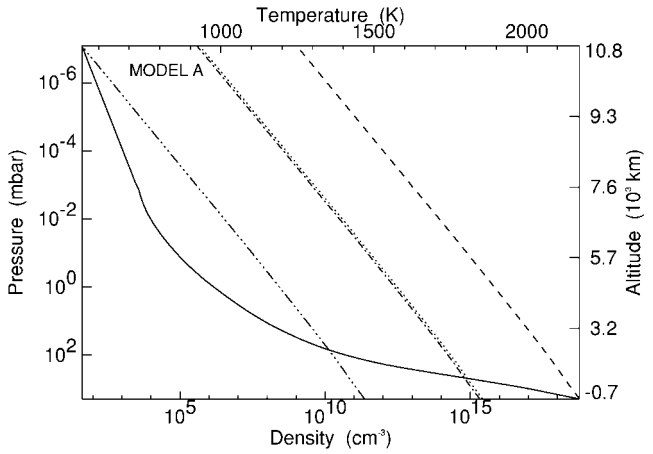

FIG. 1.—Vertical profile of temperature (*solid line*), total density (*dashed line*), and initial constituent number densities (H_2O: *dotted line*, CO: *dash-dotted line*, CH_4: *triple–dot-dashed line*).

Model atmosphere.—Three models are investigated in this Letter. Our reference model using solar abundances is shown in Figure 1 (model A). We also consider two other cases, model B and model C, in which H_2O and CO abundances are 10 times lower, respectively. We have taken the 1 bar level to be "0" km, and all heights are referenced from this level. The temperature-pressure profile and chemical abundances are based on Seager, Whitney, & Sasselov (2000), in which the heating from stellar irradiance is uniformly distributed on the whole planet and in which clouds (that absorb and scatter light) are not considered. The temperature decreases from the bottom to the top of the atmosphere. The abundances of CO and H_2O are 3.6×10^{-4} and 4.5×10^{-4}, respectively. The H_2O, CO, and CH_4 abundances are determined by the thermodynamic equilibrium chemistry in the deep atmosphere, using solar abundances. For CH_4, we adopt the value 3.9×10^{-8}, which is the lower end of the model by Seager & Sasselov (2000). The temperature-pressure profiles are not certain because the global circulation and high-temperature condensation (Seager & Sasselov 2000; Sudarsky, Burrows, & Pinto 2000) are not constrained in generating the model atmosphere. Various temperature-pressure profiles have been verified and will be presented in a more comprehensive paper. The eddy diffusion is proportional to $n^{-\alpha}$ (n is the number density), where α is taken to be ~0.6–0.7.

3. RESULTS

3.1. OH *and* O *Radicals*

Figure 2 shows the OH and O radicals in our models. OH and O are the most important radicals since they drive most of the chemical reactions. O is the most important element in facilitating the formation of OH radicals in the water-poor atmosphere. These species are produced photochemically; for example,

$$CO + h\nu \rightarrow C + O,$$

$$H_2O + h\nu \rightarrow H + OH.$$

CO photolysis is an important source of O and H_2O is the main source of OH. O is increasing with altitude as a consequence of

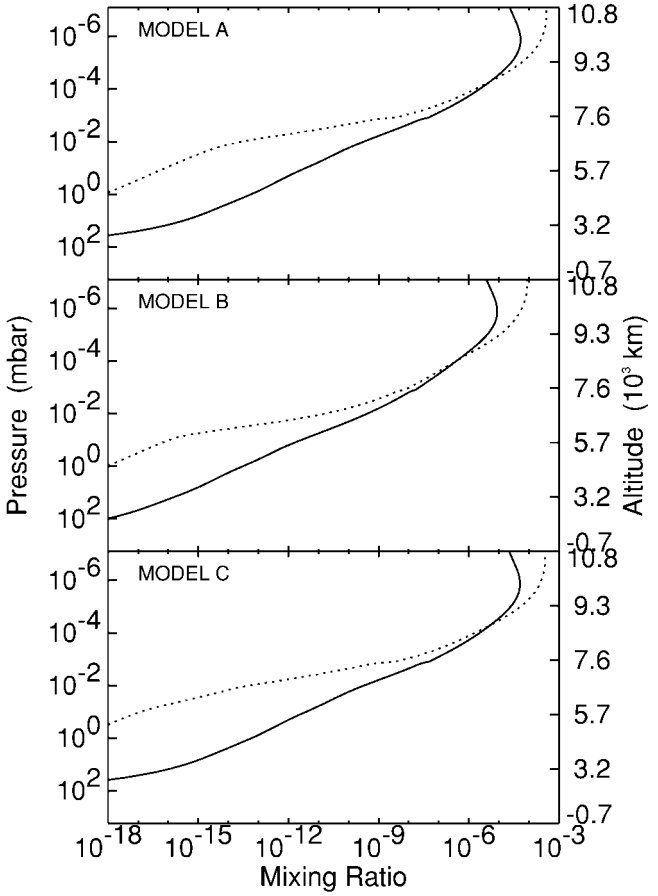

FIG. 2.—Comparison of mixing ratios of OH (*solid line*) and O (*dotted line*) radicals in models A, B, and C.

H_2O and CO photolysis. OH is increasing with altitude until it starts decreasing at ~10 nbar. The decline of OH above 10 nbar is due to OH photodissociation. We see that the mixing ratio of OH radicals is not sensitive to the abundance of CO and H_2O. With an order-of-magnitude change in H_2O (model B) or CO (model C), OH is changed by only a factor of $\lesssim 3$. However, O is sensitive to both CO and H_2O concentrations and preferentially forms OH. From Figure 2, we see that OH is not sensitive to H_2O abundance. The abundance of H_2O depends on the comparative richness of cosmic C and O. Under high stellar UV irradiation, a fraction of CO will be photodissociated. The resulting O will react with H_2 to form OH, which eventually forms H_2O by reacting with H_2.

3.2. CO_2 *and* CH_4

CO_2 is formed mainly via the reaction of CO and OH. Figure 3 shows the vertical profiles of CO_2 for our three models. The CO_2 mixing ratio is enhanced in the upper atmosphere. At pressures of ~10 nbar for model A, the CO_2 mixing ratio is only about 2 orders of magnitude less than its progenitor, CO. The CO_2 abundance in the model is rather insensitive to the abundance of H_2O. An order-of-magnitude decrease in H_2O results in only a factor of ~3 decrease in CO_2 abundance (see models A and B in Fig. 3). However, CO_2 abundance varies approximately linearly with the abundance of CO (see models A and C in Fig. 3).

The formation of CH_4 is initiated by the downward flux of

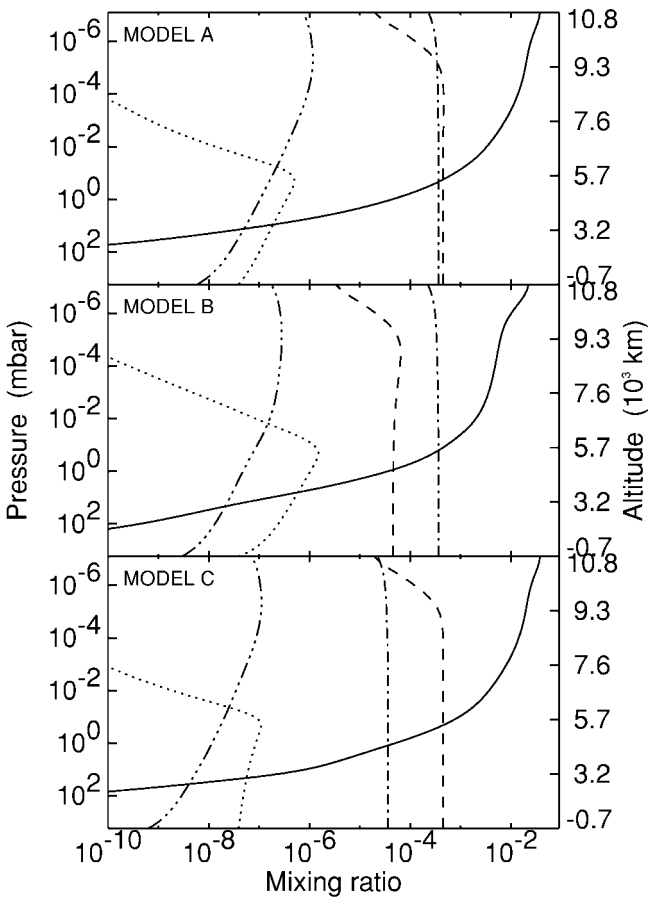

FIG. 3.—Comparison of mixing ratios of H (*solid line*), CH_4 (*dotted line*), H_2O (*dashed line*), CO (*dash-dotted line*), and CO_2 (*triple–dot-dashed line*) in models A, B, and C.

C atoms produced in the photolysis of CO in the upper atmosphere. This obtains the following sequence of reactions:

$$CO + h\nu \rightarrow C + O,$$

$$C + H_2 + M \rightarrow {}^3CH_2 + M,$$

$$2\,{}^3CH_2 \rightarrow C_2H_2 + 2H,$$

$$C_2H_2 + H + M \rightarrow C_2H_3 + M,$$

$$C_2H_3 + H_2 \rightarrow C_2H_4 + H,$$

$$C_2H_4 + H + M \rightarrow C_2H_5 + M,$$

$$C_2H_5 + H \rightarrow 2CH_3,$$

$$CH_3 + H + M \rightarrow CH_4 + M.$$

Figure 3 shows the vertical profiles of CH_4 in our models. We see that the CH_4 mixing ratio is increasing by a factor of 5–100 from the bottom to the 0.1 mbar level (see Fig. 3). Above this level, CH_4 rapidly decreases because of photodissociation.

The CH_4 mixing ratio is increased by a factor of ~2 when we lower the H_2O abundance by an order of magnitude (see models A and B in Fig. 3). We suggest that this increase is due to less UV shielding by water above. The CH_4 mixing ratio is decreased by an order of magnitude when we lower the CO abundance by an order of magnitude. The reason is that CO photolysis is the source of the C in CH_4.

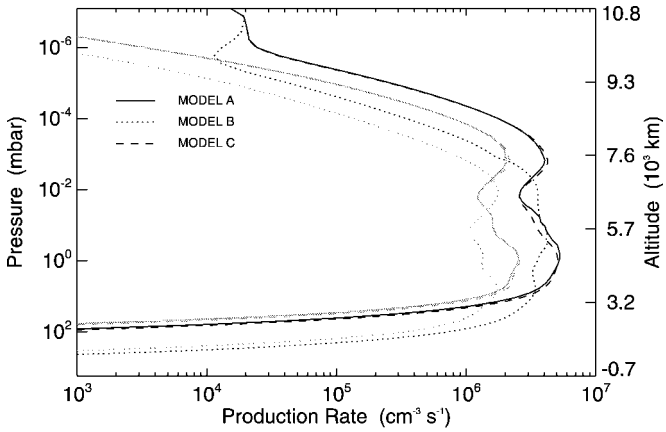

FIG. 4.—Production rate of H (*black lines*) and photolysis rate of H_2O (*gray lines*) in models A, B, and C.

3.3. H *and* H_2O

Figure 3 shows the mixing ratios for H and H_2O. The most striking feature is the production of H (all three models). In our one-dimensional model, the production rate of atomic hydrogen is not sensitive to the exact abundances of CO and H_2O. With an order-of-magnitude change in the abundance of either CO or H_2O, the atomic hydrogen changes by only a small factor, ~1–2. This implies that the production of H in the three models is limited by the availability of UV photons. The H production is also not sensitive to the abundance of CH_4. CH_4 abundance has been increased to be as high as CO, and the H mixing ratio is only changed by a small factor. However, temperature-pressure profiles can significantly modify the H production. A more comprehensive discussion will be given in a separate paper (M.-C. Liang et al. 2003, in preparation). The mixing ratio of H exceeds 1% at the top of atmosphere. At the top of the atmosphere (<1 nbar), H_2 will be photolyzed and is a source of H. This atomic hydrogen will fuel the hydrodynamic-loss process, as suggested by Vidal-Madjar et al. (2003), and is discussed in more detailed in the companion paper by C. D. Parkinson et al. (2003, in preparation).

Figure 4 shows the production rate of H and the photolysis rate of H_2O. The rates are not sensitive to the abundance of CO but are sensitive to the abundance of H_2O. By comparing the H_2O photolysis rate with the H production rate, it is evident that production of H is mainly driven by H_2O photolysis and the reaction of OH with H_2. Below ~1 mbar, HCO plays a role in the removal of H via

$$CO + H + M \rightarrow HCO + M,$$

$$HCO + H \rightarrow CO + H_2.$$

In the upper atmosphere, H atom recombination and reactions with CH and $^3CH_2$ will drive the loss of H via

$$2H + M \rightarrow H_2 + M,$$

and

$$H + CH \rightarrow C + H_2,$$

$$H + {}^3CH_2 \rightarrow CH + H_2,$$

$$C + H_2 + M \rightarrow {}^3CH_2 + M.$$

The timescale for producing H is on the order of 10^5 s, ~1 day. Since the planet is suggested to be tidally locked, the temperature difference between day and night sides could be as high as ~1000 K. Hence, the wind speed is a few kilometers per second (Showman & Guillot 2002; Cho et al. 2003). The global circulation timescale is calculated to be about 1 day. So the mixing ratio of the produced H is overestimated.

4. CONCLUSION

We have considered a series of possible chemical reactions using various models for a "hot Jupiter." We have shown the mechanism for producing atomic hydrogen. The production of H is *insensitive* to the exact abundances of CO, H_2O, and CH_4. Lowering H_2O or CO by an order of magnitude changes the concentration of H by only a factor of $\lesssim 2$. However, the production rate of H is sensitive to the temperature profile. A 30% change in the temperature will result in an ~50% change in the H concentration.

Our calculations show that the H mixing ratio at ~1 mbar is $\sim 10^{-3}$ and exceeds 1% in the top of the atmosphere. Being less gravitationally bound, the atomic hydrogen formed at the top of atmosphere can escape hydrodynamically as putatively suggested by the observations of Vidal-Madjar et al. (2003). Since these close-in gas-rich giant planets are probably tidally locked, it is of interest to simulate the differences in chemical processes between the day and night sides and the global transport of heat and mass as well. In addition, high-temperature condensations and strong UV absorbers other than H_2O are other important factors in controlling the evolution and chemical reactions in the atmosphere.

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